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Superconducting Fault Current Limiters for HVDC Systems

Xiaoze Pei, Alexander C. Smith and Mike Barnes

School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, UK

Abstract

High-voltage direct current (HVDC) transmission systems using Voltage-Source Converters (VSC) are widely recognized as offering significant potential for long distance high power delivery, particularly for offshore wind farm connections. One of the barriers for the development of multi-terminal HVDC systems is the lack of technologies which enable direct fault isolation. This paper will investigate DC fault current limiting technology to reduce fault currents to acceptable levels allowing DC circuit breakers to operate quickly and reliably. Superconducting fault current limiters (SFCL) are a promising candidate, satisfying most of the ideal fault current limitation requirements. This paper shows the potential for reducing the fault current to more acceptable levels using SFCLs in VSC-HVDC systems. A summary of the advantages and disadvantages of resistive and inductive SFCLs is also given. An SFCL limits DC fault current very effectively, reducing the fault current the HVDC circuit breaker would have to interrupt. The paper includes a detailed analysis of resistive and inductive SFCLs including aspects of practical design for use in commercial VSC-HVDC systems. Finally, key issues such as cryogenic cooling and superconducting material costs are highlighted.

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Keyword: HVDC, Multi-terminal, Inductive SFCL, Resistive SFCL

1. Introduction

The UK renewable energy roadmap identified offshore wind as a key technology to enable the UK to meet the 2020 renewable energy targets. Up to 18 GW of offshore wind capacity is planned by 2020 subject to cost reductions, corresponding to around 17% of the UK's net electricity production [1]. Traditional AC power system connections are not economic for long distance transmission beyond typically 80 km. Cost effective transmission networks are crucial to accommodate and integrate offshore renewable energy. Voltage source converter (VSC)

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high-voltage direct current (HVDC) transmission system is widely recognized as offering the greatest potential for long distance high power delivery [2-4]. Multi-terminal DC networks and mesh DC grids improve system stability, reliability and reduce asset cost [5]. One of the major disadvantages of DC networks however is direct circuit breaking becomes difficult because unlike AC systems, breakers cannot use the natural current-zero to isolate any fault on the circuit. Fault isolation on simple point-to-point HVDC systems still commonly relies on AC breakers placed on the AC side of the interconnector stations [4]. If fault isolation on multi-terminal DC networks rely on AC breakers, the entire DC network has to be de-energized. The fault can only then be isolated using fast isolation switches; the remaining DC networks can then be re-energized and return to normal operation. This takes significant time to clear the fault and this is unacceptable for large HVDC systems. Technologies which provide direct fault isolation on DC networks are seen therefore as a key priority [4]. ABB has been working on the development of hybrid HVDC circuit breakers, which combine the advantages of low-loss normal operation and a fast current interruption capability [6, 7]. Alstom grid is developing an ultra-fast mechatronic circuit breaker [8]. There is however no commercial installation of a DC circuit breaker operating on a VSC-HVDC system to date.

This paper will investigate DC fault current limitation technologies to reduce fault currents to acceptable levels allowing the DC circuit breakers to operate quickly and reliably. Ideal fault current limiter (FCL) requirements for HVDC systems can be summarized as follows [9, 10]:

- Minimum impedance during normal operation. Resistance of the FCL duringthe normal state would produce extra heating.
- Fast fault current limitation. The FCL is required to change to high impedance in a short time and reduce the peak fault current level and/or the rate of the current rise.
- Quick and automatic recovery. It is desirable to reclose onto the DC networks as soon as possible after a fault has been cleared.
- Fail safe. The FCL would still limit the fault current even if it fails.
- Compact structure, small footprint and light weight. This is extremely important if the unit is planned to be installed on an offshore platform.
- Applicable at high DC voltages.
- Cost effective.

A superconducting fault current limiter (SFCL) is potentially an attractive candidate for this application and satisfies most of the requirements [9-11]. SFCLs can operate naturally and quickly to prevent the increase in the fault current, limiting the DC fault current to more acceptable levels. Superconducting materials are ideal for DC networks since there are no losses for pure DC current making them virtually invisible to the system when operating normally. The application of SFCLs for HVDC systems has received very limited attention though.

Existing SFCL topologies will be examined and compared. Generally speaking, superconducting fault current limiters can be divided into resistive and inductive types. At present, the majority of SFCLs under field test are resistive SFCLs and inductive saturated iron-core SFCLs [12-15]. A resistive SFCL is the simplest and most compact design making use of the intrinsic superconductor material behavior of quenching at high current levels and transitioning from negligible resistance to a high resistance to limit the current. During normal operation, SFCLs remain in the superconducting state and the resistance is almost negligible. When a fault occurs and the current rises above the critical current of the superconductor, the material transitions rapidly from the superconducting state into the normal resistive state to limit the fault current level. This is automatic and repeatable [11]. Inductive SFCLs reduce the transient current rise inductively and allow more time for DC circuit breakers to operate. The stored energy in the networks however is increased due to the extra inductance added to the circuit. This increases DC circuit breaker voltages, energy absorption requirements, and fault clearance times. This paper will elaborate and discuss the advantages and disadvantages, along with the design challenges for resistive and inductive SFCLs for operation in VSC-HVDC systems.

2. Superconducting Fault Current Limiters

2.1. Resistive SFCLs

A resistive SFCL is the simplest and most compact SFCL design which directly uses the natural characteristics of the superconductor material. The schematic circuit of a resistive SFCL is shown in Fig. 1 [10]. A resistor or inductor is normally placed in parallel with the superconducting element to avoid overvoltage if the resistance of the superconductor increases too rapidly after a fault occurs. During normal operation, the superconducting element carries the full DC current in the superconducting state with negligible resistance. Once a fault occurs, the current through the superconductor increases quickly. When the current in the superconductor exceeds the critical current level, the superconductor quenches and develops resistance, limiting the fault current level. The resistance of the superconductor increases quickly and therefore a high percentage of the fault current is diverted into the parallel resistor or inductor which helps to limit the fault current.

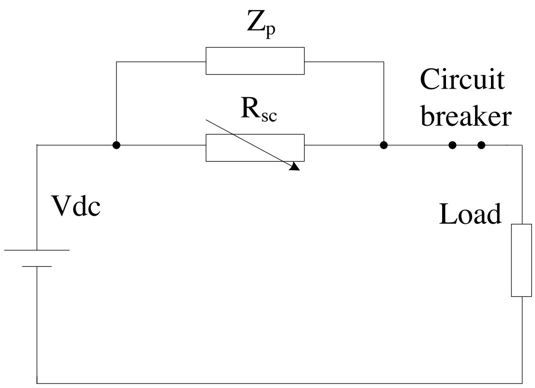

Fig.1. Electric circuit of a resistive SFCL with parallel impedance

Resistive SFCLs have been extensively investigated and tested for AC power networks [12, 13, 16]. A single phase 138 kV, 0.9 kA resistive SFCL was successfully developed and tested at Southern California Edison power network in October 2011. This demonstration project was sponsored by the U. S. Department of Energy (DoE). The fault current level was reduced by more than 50% [17].

Resistive SFCLs in VSC-HVDC systems have also been looked at and simulated [18-20]. The simulation results show that a resistive SFCL can limit the fault current effectively. These studies also demonstrate that the resistive SFCL is a promising candidate for protection and system stability. Resistive SFCLs working together with DC breakers have been experimentally tested for a 400 V DC system [22, 23]. The resistive SFCL limits the fault current to within several hundred amps and then the circuit breaker breaks the current. It is possible for this structure to be applied in HVDC systems.

A concept design of a resistive SFCL for ±200 kV/1.5 kA DC transmission system was undertaken [24]. High temperature superconductor (HTS) Yttrium Barium Copper Oxide (YBCO) tapes were used in the non-inductive coil. Each coil was made of 54 meters of YBCO wire. 8 non-inductive coils were connected in parallel to provide the current capacity and then 40 coil-groups were connected in series to provide enough resistance. The quench resistance was approximately 15 Ω. Approximately 17 km of YBCO wire would be needed in this resistive SFCL unit.

2.2. Inductive SFCLs

There are two types of inductive SFCLs: shielded iron-core SFCLs and saturated iron-core SFCLs. A shielded iron-core SFCL consists of an iron core, a normal conducting primary winding, and a secondary winding made of a superconducting cylinder. This topology was abandoned due to the bulky iron core and the challenge of making the superconducting cylinder quench uniformly [25].

The inductive SFCL discussed here refers to the saturated iron-core type. A saturated iron-core SFCL is shown in Fig. 2 [14, 26]. It consists of two iron cores, which are driven into saturation by a DC bias supply. Two iron cores are used so that the unit can limit the current in both directions. During normal operation, the iron cores are fully saturated because the normal operating current is much lower than the DC bias current. The inductances of L1 and L2 are small because in saturation they are similar to air core inductors. When a fault occurs, the increased fault current will drive coil L1 or L2 out of saturation depending upon the current flow direction and the operating region of the core returns back to the high permeability region. This causes the inductances of the coils to increase which reduces the rise of the fault current.

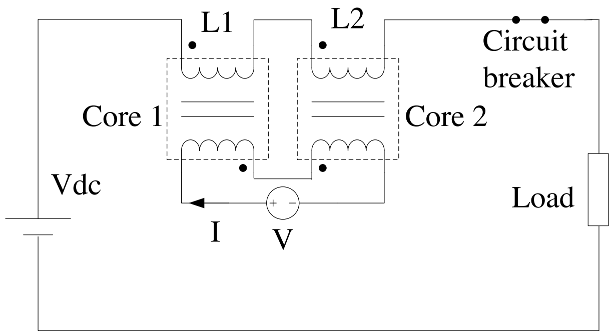

Fig.2. Electric circuit of an inductive saturated iron-core SFCL

Zenergy Power have been investigating the saturated iron-core SFCL. A 15kV/1.2kA SFCL was installed and successfully tested on the grid controlled by Southern California Edison since March 2009 [27]. After successful testing of the demonstrator SFCL, Zenergy Power designed a 12kV/1250A SFCL which was planned to be installed in a CE Electric UK substation. A 138 kV/1.3kA SFCL using the same concept was expected to be installed in the AEP Tidd substation in early 2012 [27]. However, the project was terminated in September 2011 [12].

Innopower developed a three-phase 35 kV/90 MVA saturated iron-core SFCL [15]. This SFCL consisted of six rectangular cores and a central core which are all placed in a single cryostat. The SFCL was installed in the Puji substation operated by the Southern China power grid in 2007 for live grid operation [29]. The SFCL demonstrated encouraging current-limiting performance. The artificially imposed fault test on the live grid showed good agreement with the design expectations [29]. A three-phase 220 kV/300 MVA saturated iron-core SFCL has been successfully manufactured and installed at Shigezhuang substation in Tianjin, China [15, 30].

2.3. Comparison of SFCLs for HVDC systems

All the installed SFCL projects to date are for AC power networks; there are no prototype or installed units on HVDC system yet. Resistive SFLCs and inductive SFCLs will be compared in this section.

The advantages of resistive SFCLs are summarized as follows:

- Compact structure, simple design and light weight. A resistive SFCL coil is an air-cored coil which can be designed as a lightweight unit.
- Automatic triggering. The superconductor automatically quenches when a fault occurs and a trigger signal isnot necessary.
- Fast and effective fault current limitation. The superconductor will quench once the fault current exceeds the critical current and the developed resistance will limit the fault current quickly and effectively.
- Intrinsicallyfail safe. The superconductor will burn out if it fails to limit the fault current (i.e. open circuit).
- Variable coil inductance. The SFCL coil inductance depends on the winding topology and can be designed either for minimum inductance or for a finite inductance value. This can have certain operational benefits.

The disadvantages of resistive SFCLs are:

- Long lengths of superconducting wire required. This is related to the required quench resistance and the temperature rise on the superconductor wire. The conceptual design for example for a resistive FCL for ±200 kV/1.5 kA DC transmission system needed 17 km of YBCO wire [24].
- Hot spot problems. It is impossible to guarantee all parts of the superconductor will quench at the same time. The quench normally starts at some point on the wire which can lead to hot spots.
- The high energy dissipated in the SFCL coil. When a fault occurs, the SFCL coil quenches and becomes resistive to limit the peak fault current level, and high joule losses are dissipated in the superconductor before the fault clears.
- Long recovery time. Due to the heat dissipated and resulting temperature rise of the superconductor wire, it may take several seconds to several minutes to recover.
- A room temperature/cryogenic interface is required for the current connections from the device to the external power system. The worst case fault scenario is that the two current feedthroughs would see the full DC voltage. This poses technical challenges for the feedthrough design at cryogenic temperatures and the cryogenic environment. The space required to handle high voltages in the cryogenic environment makes these systems large. The current leads also produce extra losses and may introduce a thermal insulation problem.

The advantages of inductive SFCLs are summarized as follows:

- Inherently fail safe. If the DC bias supply fails, the iron-core will be de-saturate and the primary windings will produce a high inductance to limit the current.
- Fast recovery. After the fault clears, the unit recovers immediately because the coil remains in the superconducting state during the fault.
- Does not require a room temperature/cryogenic interface in the power line. This is useful for high voltage designs.

The disadvantages of inductive SFCLs are summarized as follows:

- Bulky and very heavy due to the need for iron cores. The installation volume of the three-phase 200 kV/300 MVA saturated iron-core FCL manufactured by Innopower was 8×8×9 m^3 in volume and has a total weight of 120 tons [15]. These volume and weight ratings are commonly unacceptable for an offshore platform.

- Significant losses in the primary windings and iron cores during normal operation.

- Complex current supply for the superconducting winding. It has to be careful not to introduce any currents into the DC bias coils, which could induce a high voltage across the superconducting coils and potentially damage the DC bias supply.

3. Key issues

3.1. Cryogenic cooling system

Superconductor materials do not incur losses operating with pure DC current; however, the superconductor material suffers from hysteretic losses in the presence of time varying field or currents. The DC system is normally connected to the AC grid using voltage source converters which can introduce a ripple current into the direct current system. For example, if the effective DC current is 2 kA, with a ripple efficiency of 1.5%, the total loss in the superconductor from the fundamental up to the tenth harmonic is approximately 0.13 mW/m [31]. If 2 km of superconductor cable was used in the resistive SFCL, the total superconductor losses would be 0.26 W which seems to be extremely low. However, the cooling efficiency of superconductors operating at cryogenic temperatures is limited. The superconductor normally operates between 4 K and 80 K. The cryogenic cooling (refrigerator) system is essential to achieve low operation temperature. The refrigerator absorbs the heat flow from the cold temperature and rejects the heat flow to the surrounding ambient temperature. Refrigerator systems require power to remove the thermal load from low temperature region. The efficiency of the refrigerator in the steady state is defined as the heat is removed from the cold temperature over the net input power required to operate the refrigerator. The efficiency of current cryogenic refrigerators however is quite low but has been improving steadily over the last decade.

State-of-the-art refrigerator systems have been discussed in [25, 32]. Refrigerator systems for 4K to 80 K temperature ranges include the recuperative types (steady flow) and the regenerative types. Examples of the recuperative types are the Joule-Thomson, Brayton and Claude cycles. The regenerative types include: Stirling, Gifford-McMahon (G-M) and pulse tube cycle. The G-M cryocooler is the most popular type for cooling superconductors in power applications. Maintenance of these systems in normally undertaken about once a year. The refrigeration power at 80 K range from about 10 W to 500 W requiring an input power rating from 800 W to 10 kW. For example, the Cryomech AL600 cryocooler provides cooling power of 100 W at 30 K or 600 W at 80 K [34]. The net input power required however to operate the cryocooler is 11.5 kW at 50 Hz. In this case, the efficiency of the AL600 cryocooler at 30K is only 0.87% whilst the efficiency at 80 K is 5.21%. This means that significant input power is needed to remove small heat losses at 30K. The cryocooler capital equipment investment, maintenance costs, operational noise, volume and weight also need to be taken into consideration.

The input power required for a cryocooler may not be a significant problem for HVDC systems. However, two SFCLs would be needed for each end of a symmetric monopole or bipole HVDC system. The capital cost to build the offshore platform to house the cryocooler would also be expensive.

3.2. Superconductor cost

The cost of HTS materials is still the biggest obstacle for large-scale power applications. In power equipment, copper wire typically costs in the range 15$/kAm to 25$/kAm, which sets the target for superconducting wire development. Approximate present day costs of high temperature superconductor are illustrated in Table 1. The use of superconductors in power applications will grow exponentially if the cost of the superconductor is lower than 50 $/kAm [35]. Amongst the main superconducting materials available today, Magnesium Diboride (MgB_2) offers the greatest opportunity cost. Magnesium Diboride (MgB_2) wires manufactured by Columbus Superconductor normally have copper, copper nickel or monel sheaths. They have better thermal stability but a lower quench resistance. They have been used to date mainly in medical application such as magnetic resonance imaging (MRI) machines. Columbus Superconductor is currently working on developing MgB_2 wire with a high quench resistance, more suitable for fault current limiters. Power applications require lower cost superconductor materials, but suppliers require more demand to reduce the cost. It has been predicted that some economic superconducting products are likely to appear by the 2020s [25].

Table 1. Approximate high temperature superconductor cost

Material	Nominal operating temperature (K)	Approximate material cost ($/kAm)
BSCCO	77	180 [35]
YBCO	77	400 [36]
MgB_2	25	13 [37]

4. Conclusions

Multi-terminal VSC-HVDC systems have been identified as one of the key technologies to develop offshore wind farm connections. Fault current levels are one of the barriers for this technology. This paper demonstrates the potential for reducing fault currents to more acceptable levels using SFCLs in VSC-HVDC systems. Resistive and inductive SFCLs are compared. Resistive SFCLs are thought to be more suitable for HVDC systems. The key issues such as the cryogenic cooling system and superconductor material cost are highlighted. Practical SFCL systems are predicted to become realisable by the 2020s.

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